

Interferometry

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KEY POINTS ON INTERFEROMETRY

- The extension of multi-telescope interferometry and aperture synthesis to infrared and optical wavelengths will enable in this decade significant progress in stellar and galactic physics, and will lead to great interferometric infrared/optical arrays of the future.
- The real-time correction of atmospheric turbulence with adaptive optics will allow the new generation of large telescopes to reach several magnitudes fainter, and to resolve spiral arms of galaxies anywhere in the universe.
- Laser interferometer gravitational wave detectors on earth and in space in this decade and the next can probe the dynamics of relativistic systems in the galaxy and the early universe.

Introduction

In this decade, the first infrared/optical interferometer arrays, adaptive optical systems, and laser interferometer gravitational wave detectors will be developed, implemented, and employed for fundamentally new types of observations. These new instruments will undertake systematic imaging in the infrared and visible of stellar surfaces and circumstellar material and of bright galactic nuclei, and will search for gravitational radiation from neutron stars and other condensed objects.

In the first decade of the next century, we foresee construction of great interferometric observatories on the earth and in space, performing astrometric measurements to microarcsecond precision and obtaining imagery of the faintest sources with angular resolution substantially better than 1 milliarcsecond. We also forecast the opportunity for an ultrasensitive, gravitational wave detector in space, designed for detailed observations of individual systems, and for detection of subtle gravitational wave tracers of the early epochs of cosmological history.

These instruments and observatories will be possible as a result of recent advances in optics, metrology and precision control, as well as improved understanding of gravitational wave sources and of atmospheric turbulence.

Overview of the Programs*Infrared and Optical Interferometry*

Astronomers are increasingly aware of the opportunities which IR/Optical interferometry will offer. Following rapidly the path which radio astronomers traveled 20 years ago, optical interferometry is now



Figure 1. (Left) Optical interference fringes observed with an aperture mask (4.5 meter baseline) on a conventional telescope (Readhead et al 1988); (Middle) between subapertures on the Multiple Mirror Telescope (Hege et al, 1985); (Right) between independently mounted telescopes (15 meter baseline) at the CERGA observatory in France (Koechlin, 1984).

being carried out, albeit in a limited way. Aperture synthesis, which combines beams from multiple apertures to achieve the resolution of a much larger aperture, has been extended to the optical regime. Already an astrometric interferometer operates regularly on Mt. Wilson, actively controlled with a precision exceeding the optical tolerances of many large telescopes, while nearby an infrared interferometer monitors the formation of dust in the shells of stars. Interferometry is the most accurate technique for measurement of stellar diameters, with results from France, Australia, and most recently in the United States surpassing the accuracy of lunar occultation techniques.

Infrared/Optical interferometry will have a profound impact on astronomy. Current seeing and aperture limits to resolution will be surpassed by orders of magnitude. Telescope arrays planned for this decade may revolutionize stellar astronomy, yielding unprecedented detail about stellar surfaces, atmospheres, shells, companions, and winds. These future instruments will allow imagery with *msec* resolution of oblateness of rotationally distorted stars, of chromospheric structures, of jets from young stellar objects, and of narrow line emission regions in Seyfert galaxies. Arrays of the next decade, on the ground and in space, will advance IR/optical interferometry to a sophistication comparable to that achieved by the radio astronomy community in the Very Large Array.

Interferometry also promises remarkable opportunities for astrometry. Already ground-based interferometry is approaching a precision of 1 *msec*. Space missions of the 1990's and beyond should improve this performance initially by at least two orders of magnitude. It will be possible to determine an accurate parallax for any observable point source in the galaxy, and to measure proper motions of stars throughout the galaxy and the local galaxy group.

Numerous research groups, including several in the U.S., have initiated construction of arrays of two or three telescopes for imaging interferometry and astrometry in the visible and infrared. We recommend significant support, to assist rapid continued progress in this area. Specifically, we recommend support for a range of facilities operating in the visible and infrared with small and medium-aperture telescopes. Such breadth of activity is critical to the development of the field. By the end of the decade it will be essential to have in operation an array of five or more telescopes of medium aperture (1.5-2.5 meters). This array is required to achieve important infrared science objectives, to fully develop interferometry in the extreme multi- σ condition, and to serve as a critical stepping stone to a very large optical array. This array of medium apertures will extend the reach of interferometric imaging to many YSO's and galactic nuclei, returning the science and technical experience needed for developments of the next decade.

As with radio interferometry, IR/optical interferometry will reach its full potential with large, well populated arrays of moderate to large aperture telescopes. We therefore recommend, for the latter part of the decade, the development of a plan for a Very Large Optical Array, to be built in the period 2000-2005. Composed of perhaps 20 medium-aperture telescopes, each equipped with adaptive optics, this array will achieve aperture synthesis imaging with sub-*msec* resolution of active galactic nuclei, novae, stellar accretion disks and QSO's.

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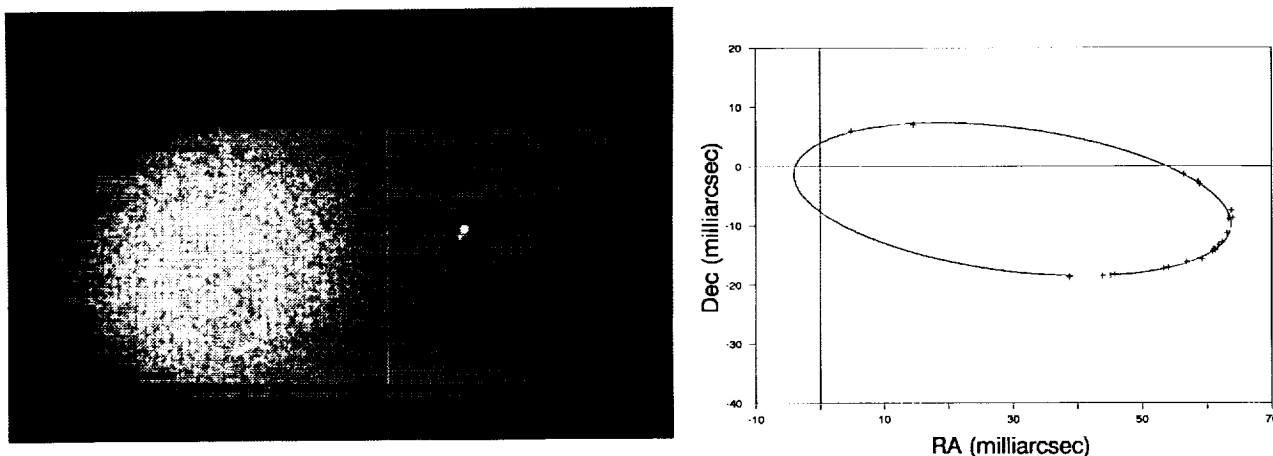


Figure 2a (left). Optical aperture synthesis image of the binary σ Her. (Left) A long time exposure, seeing disk diameter about 2". (Middle) The image reconstructed with closure phase relationships, printed at the same scale. The separation is 70 m sec, the dynamic range 30:1. (Nakajima et al, 1989)

Figure 2b (right) The orbit of the binary star β Ari, determined from interferometric measurements recorded with the Mark III interferometer. Maximum separation about 65 m sec. (Pan et al, 1990)

In the moderate cost category we recommend an astrometric interferometric space mission. This mission should offer a capability to achieve precision astrometry of the brightest stars in nearby galaxies. A number of concepts have been proposed, some based on interferometers that can also be used for imaging while others are dedicated astrometric devices. All support the expectation that interferometric techniques will yield astrometric precision on the order of 3-30 μ sec over the entire sky.

The ultimate interferometric performance will be achievable above the atmosphere, beyond the limits imposed by atmospheric absorption, scattering, and turbulence. A modest array, operating in the ultraviolet, could image objects as faint as 20th magnitude with resolution of a few m sec, particularly useful for study of galactic nuclei. We recommend planning and preparation for both an intermediate sized imaging interferometer and an advanced array. The astrometric mission of the 1990's should demonstrate many of the metrology and control techniques required for future advanced arrays in orbit and on the lunar surface. Other aspects will be developed in the work on ground-based arrays. There remain issues that require further study, and we recommend an effort in development of this technology for the next decade.

The United States is considering a major commitment to the establishment of a permanent human presence on the moon. NASA, recognizing the outstanding merits of the lunar surface for interferometry, has recommended optical and sub-millimeter arrays for early implementation on the lunar surface. In the context of a broad lunar program, we endorse this plan. The moon offers a uniquely large and stable platform. A Lunar Optical Array should have a large number of apertures and long baselines. In the earliest phase, a small number of operational telescopes could be activated, perhaps optimized for a high priority capability such as high dynamic range imaging or sub- μ sec astrometry, with such science goals as detection and study of planets in other systems, or measurement of the accretion disks in active galactic nuclei. In subsequent years, additional telescopes could be added to reach the final configuration, offering imaging of the faintest sources.

Adaptive Compensation for the Atmosphere

The terrestrial atmosphere has been and remains a primary limitation to observational astronomy. The possibility of removing the effects of atmospheric turbulence has long been considered, but only now are the necessary sensitive detectors and fast, reliable electronics becoming available at moderate cost. With the emergence of adaptive optics for solar and stellar imaging, adaptive techniques appear certain to play a major role in ground-based astronomy of the 1990's.

Adaptive optics (AO) will become a standard component of large telescope systems (≥ 4 meters) during the next decade. It will perform most effectively and generally in the infrared, where near-diffraction limited operation will be possible over a substantial angular field with relatively modest AO systems. Moving toward the visible, the corrected field will decrease, probably to a few arcseconds, and the cost of the optical system will increase. Although not applicable to all observational problems, AO will offer significantly improved resolution and increased sensitivity for many applications. It will provide a dramatic gain in angular resolution, and will increase the efficiency of high resolution spectrographs. These gains will be invaluable in many areas, for example the study of young stars and of galactic nuclei.

Adaptive optics is ripe for implementation in astronomical instruments. We recommend a program to apply to astronomy (often by simplification) adaptive optics technology which has already been developed under DOD support. The development of technology for laser reference techniques should continue. The DOD has developed a momentum in the field which astronomers will wish to preserve and steer to their benefit. We recommend the immediate implementation of adaptive correction technology to selected existing large telescopes. This will yield improved image quality at all wavelengths over the whole sky, but most dramatically and with assured significant scientific return in the near infrared.

Although the last decade has seen rapid progress in adaptive optics technology, many technical and cost tradeoffs critical to astronomy remain unstudied. During the early years of the decade, experience with first generation adaptive systems will lead to an adequate characterization of the atmospheric parameters critical for adaptive optics - seeing, time constant, and isoplanatic angle. This will provide the basis, later in the decade, for optimized systems functioning effectively in the visible range for many applications.

Gravitational Wave Observatories

The theoretical basis of gravitational radiation is well established, and the mathematical formalism and our astrophysical knowledge are now adequate to estimate the emission from many known and hypothesized astrophysical sources. Strong gravitational radiation is expected from individual binary systems composed of condensed components such as white dwarfs, neutron stars and black holes. Rotating neutron stars with an equatorial ellipticity may be detectable. A wide range of astrophysical information, accessible in no other way, may be revealed from gravitational wave observations, such as the evolution of asymmetries in the core of a supernova, and the rate at which condensed stars fall into supermassive black holes out to $z=3$.

The technology is now at hand to achieve the direct detection of gravitational waves, to measure the waveforms and determine the direction, frequency, and polarization, and to deduce the size and shape of the sources. A LIGO (Laser-Interferometer Gravitational-Wave Observatory) planned for this decade will provide a facility for the implementation of many generations of increasingly sensitive high frequency detectors. It seems likely that the LIGO will be a rich source of information about neutron stars and neutron star physics. LIGO should detect supernovae or collapse of a stellar mass to a black hole at 10 Mpc, if 0.01% of the energy of collapse is emitted as gravitational waves. It also should detect coalescence of two neutron stars out to 1000 Mpc and the merger of intermediate mass black holes out to the Hubble distance, as well as aid in determining the distance scale.

Massive objects and binaries will emit low frequency radiation which is difficult to detect from the earth, owing to terrestrial disturbances. A LAGOS (Laser Gravitational-Wave Observatory in Space) would detect individual binaries down to the confusion limited background noise of galactic and extragalactic binaries, and the merger of condensed stars with supermassive black holes at cosmological distances. LAGOS also might bring unique cosmological information with detection of relic gravitons from the early universe.

We expect the LIGO program to go ahead, with a substantial probability of direct detection of gravitational waves before or soon after the year 2000. Supernovae or coalescence of degenerate stars and/or stellar mass black holes are the most likely sources of detectable radiation. An antenna on the lunar surface would offer greatly improved discrimination of source direction. If ground-based searches for gravitational waves are successful at the expected levels, we foresee intense interest in extending the measurements to many other types of sources. The greatest return in astrophysical information about gravitational wave sources could be expected from a space observatory. With sensitivity extending to low frequencies, it might detect large numbers of compact binary systems, coalescence of condensed stars with massive black holes at cosmological distances, and a possible remnant background from the Big Bang. We recommend a planning

and technology development effort to prepare the way for a LAGOS initiative in the early years of the next century.

Summary of Recommendations

The following table summarizes the recommended programs (with LIGO omitted because it has already been approved by the National Science Board).

Recommended Programs for the 1990's		
Ground-Based Interferometry		
Large	Optical/Infrared Interferometry with Multiple Telescopes	\$50M
Medium	Adaptive Optics Development and Implementation	\$35M
Small	Planning for Very Large Optical/Infrared Array	\$3M
Space Interferometry		
Large	Interferometric Astrometric Mission	\$200M
Medium	Technology Development: Advanced Space Interferometer	\$20M
Small	Technology Development: Gravitational Wave Observatory in Space	\$20M

Infrared and Optical Interferometry

No astronomer needs to be convinced of the fantastic capability of a space-based optical and IR interferometer operating with km-length baselines and with sufficient sensitivity to produce maps of faint sources down to 0.1 msec resolution. Spatially compact phenomena of great astrophysical interest are far from simple in structure. For example, collimated jets of plasma are now known to be principal conduits of energy and mass outflow from protostars, mass-transferring binaries, and supermassive black holes. Accretion disks appear to be the main conduits of inflow in all of these objects, but we know very little of what these structures are really like. Supernova and nova explosions are highly anisotropic from their earliest stages, and the surface layers of "normal" stars seethe with starspots and flares. The development of radio VLBI has shown that the modeling of sources based on fringe amplitudes alone is far less valuable than the imaging which became possible when closure phase techniques were introduced. Our program in interferometry should aim to develop true imaging capability from the start.

Figure 3a shows the types of phenomena that can be resolved at different levels of angular resolution. The most dramatic increase in the range of accessible phenomena occurs at resolutions exceeding 1 msec, corresponding to the resolution now available with radio VLBI. With such resolution, one could not only resolve the disks of nearby main sequence stars, but could make detailed images of giant stars and of stellar winds. In the IR the structure of disks and incipient bipolar outflow in star-forming regions and the early evolution of novae and planetary nebulae could be studied. Milliarcsecond resolution will give crude structural information about the broad emission-line regions of active galactic nuclei, and detailed information about the narrow-line regions which are thought to represent the transitional zone between the active nucleus and the ISM of the host galaxy.

Resolution of 10-100 μ sec would yield a new set of breakthroughs. Not only could the broad-emission line regions of AGNs and quasars be mapped, but it would become possible to investigate the inner regions of the accretion disks themselves (in the visible and UV). Accretion disks in close binaries could be imaged, along with the mass-transferring streams which feed them. Supernovae out to the Virgo cluster could be studied as early as three months after the explosion, and surface phenomena on main sequence stars and nearby white dwarfs could be mapped.

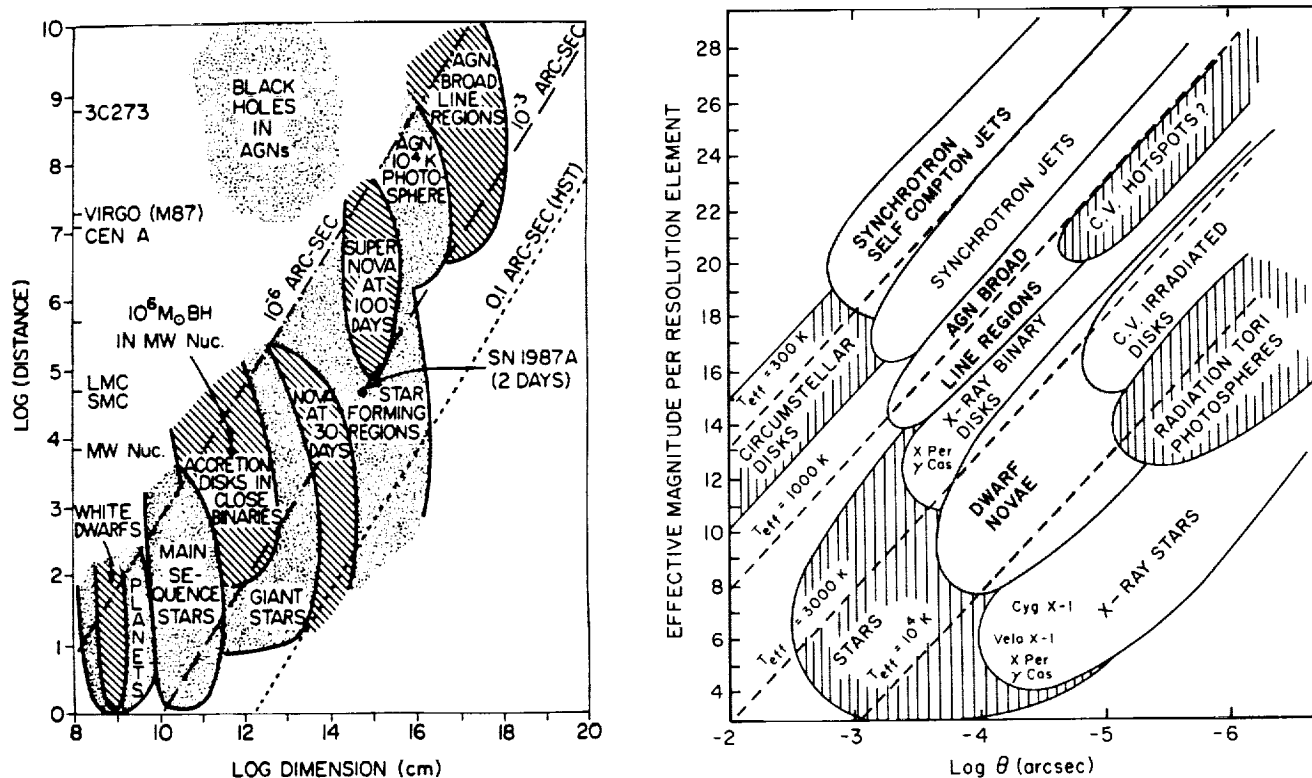


Figure 3a (left) Classes of objects and their angular sizes (diagonal lines are for constant angular size) for various ranges of size and distance.

Figure 3b (right) The required sensitivity (bolometric magnitude) for various types of objects, related to the size and characteristic temperature of an instrumental resolution element. Note that the regions begin at the lower left with the typical size of the largest members of each class.

Our justification for pursuing interferometry as a high priority must be based on these qualitative barriers which can be breached in no way other than imaging. Some goals, such as the imaging of faint AGN's at the highest resolution, will require sophisticated facilities of the future. Fortunately, simpler facilities recommended for this decade will make critical contributions toward many science goals, especially the astrophysics of young and evolved stars, bright galactic nuclei, novae, and the narrow emission-line regions of active galactic nuclei.

To be useful as an imager, a high resolution instrument must also have adequate sensitivity and dynamic range. Since phenomena associated with compact objects are often highly variable on timescales as short as minutes to hours, the time required to construct an image may also be a consideration. The bolometric brightness per resolution element may be expressed as a magnitude per pixel,

$$m \approx 43 - 10 \log T_{eff} - 5 \log \frac{\theta}{10^{-3}}$$

where T_{eff} is the effective temperature of the object being resolved and θ is the angular resolution in arcsec. The required sensitivity for various types of objects is plotted in Figure 3b. At the msec level, the required sensitivities are extremely modest: ≤ 7 th magnitude per pixel for stars and AGN, 17th magnitude for protostellar nebulae. At resolutions of 10^{-5} arcsec, a sensitivity of 28th magnitude is adequate to image objects as cool as 300 K. Even interferometric imaging of extra-solar planetary systems may be possible, although a multi-pixel image of the planet would be extremely difficult.

Requirements on dynamic range are less certain. The most stringent constraints may come from objects such as close binaries, where there is often a mismatch between the surface brightness of the mass-transferring star and that of the accretion disk. A dynamic range as large as $10^2 - 10^4$ may be required in these cases, but a smaller dynamic range may suffice to map more homogeneous structures.

Although imaging will probably prove to be the most compelling long term motivation for developing

interferometry, the most profound product of the early years of interferometry may well be ultra-precise astrometry made possible in space by freedom from terrestrial disturbances. Thus, we turn our attention to a space-based astrometric optical interferometer. Possible measurements should include proper motions, parallaxes, detection of dark companions, and relative motions in crowded fields (eg globular clusters). We expect that the instrument would have a measurement uncertainty of less than 30 μ sec. It would measure the separation of stars that are well separated, yielding absolute parallax and interconnection of reference frames.

The RR Lyrae and Cepheid "standard candles" are critical to the determination of the Hubble constant. At present, the realistic uncertainty in the Cepheid scale is about 15 percent, and it is a prime objective of HST to make a modest improvement on this accuracy. Microarcsecond parallax measurements would reduce this uncertainty by at least an order of magnitude. Quasars are generally assumed to be at "cosmological distances" and therefore to show no proper motion of their centers of mass. An instrument with a few μ sec precision could measure the relative motions of quasars, not only testing the cosmological-distance hypothesis, but also investigating the large-scale motions in the early universe.

In the area of Galactic structure, there are several applications of precision astrometry. We could measure the position, parallax, and proper motion of many of the massive young stars that mark the spiral arms. These data would map the arms without the distance uncertainty that now degrades such maps and would even show the motion associated with the density waves that are believed to be responsible for the existence of the arms. Measurements to stars within a few kpc of the Sun would yield a portion of the rotation curve for the Galaxy and thus a constraint on the mass distribution. Proper motions of the Large and Small Magellanic Clouds would make possible independent determinations of the total mass of the Galaxy and thus would tell us the amount of "dark matter" it contains.

Because of their brightness, we have an almost complete sample of the galactic globular clusters. These objects can serve as probes of the galactic potential to large galacto-centric distances. One only need measure a few stars in each cluster so as to average their typically 10 km/s motion with respect to the cluster center of mass. These measurements would also make possible the determination of the orbits of the clusters. The cluster orbital parameters could be used to investigate correlations between metal abundance, perigalactic distance, cluster radius, and orbital eccentricity, all having strong consequences for theories of the formation of the Galaxy. Finally, the membership of special stars such as Mira variables, AGB stars, helium-poor or helium-rich stars, or blue stragglers could be investigated geometrically, i.e., adding parallax to the angular position test.

Precision astrometry could be used to study stars, their formation and evolution, and their structure. Parallax measurements would substantially improve the number of accurate mass determinations for interferometrically resolved binaries, and orbits could be obtained for both components in an inertial frame, thus yielding the individual masses rather than the usual sum of the masses. Further, for nearby stars, the method of perspective acceleration could be used to determine the gravitational potential at the surface of the star. The resulting improved stellar mass and distance estimates, which would span the spectral types, would yield a sharper mass-color-luminosity relation. By concentrating on binary systems in clusters, we could empirically add age to the mass-color-luminosity relation and further test stellar-evolution models.

The study could be extended to special objects such as Eta Car, Cyg X-1, SS433, and the dozen Wolf-Rayet stars in double-lined systems that are near enough to study. The optical positions of the radio emission objects could be determined to higher accuracy than the radio positions are now determined; the spatial coincidence of these positions could thus be checked.

The astrometric determination of the wobble of a star around the star-planet center of mass would provide a sensitive means of searching for extra-solar planetary systems. Such a search, if conducted over an extended time period, would either find these systems or show them to be substantially less common than now expected, leading to a revision of our ideas about the formation of stars. Second or third generation imaging interferometers with large apertures may be able to image those planetary systems.

Astronomers are just beginning to obtain direct observational information about pre-planetary and remnant disks around young stars. Their nature and evolution can be established though high resolution near infrared studies of the material close to stars of widely different ages. These will provide a critical complement to millimeter interferometer measures of gas, which probe cooler circumstellar material at greater distances from the stellar surface. Of course, the question of the existence, distribution, and

characteristics of other planetary systems, bears directly on the question of the existence of life remote from our solar system, and the possibility that there is other intelligent life in the universe.

The deflection of light by the solar mass is one of the standard tests of general relativity. If interferometric observations near the limb of the sun are possible, microarcsecond astrometry would permit the accuracy of this test to be increased by at least three orders. Such a deflection test would approach the sensitivity needed to measure the contribution to the deflection from the square of the solar potential. According to general relativity, this term is 11 μ sec at the limb and falls as the inverse square of the impact parameter. When such a test is possible it would be the first "second-order" solar-system test of general relativity.

To summarize, the further development of IR/visible/UV interferometry should be undertaken with the goals of precision astrometry and high angular resolution imaging. Such capabilities will revolutionize many areas of astrophysics by providing the first morphological information on structurally complex systems. Attaining the goal of ultra-high resolution imagery will probably take some time, certainly longer than the nominal period to be covered in this decade survey. Fortunately, there will be important scientific returns from the earliest stages of the program.

A Ground-Based Program

Optical and Infrared interferometry is the subject of world-wide interest and activity, and the U.S. is fortunate to have several groups actively developing and using small interferometric facilities. The Berkeley Infrared Spatial Interferometer is currently operational at 10 micrometers (μ m), and is now employed to measure diameters of late type stars and map their circumstellar shells. The Mt. Wilson Mark III interferometer, operating in the visible, is in use for wide field astrometry of stars, and also for several programs to measure stellar diameters and binary orbits. The Infrared Michelson Array, at the University of Wyoming, has recently seen first light and fringes. The Infrared Optical Telescope Array is under construction, with installation on Mt. Hopkins expected in 1991. It will operate in the visible and near infrared. While each of these projects is underway, none of them is as yet adequately funded to add the critical third telescope and associated instrumentation, required for imaging applications.

In addition, several groups working with aperture masks and large telescopes have demonstrated the reconstruction of optical images by aperture synthesis from U-V plane data.

Additional arrays are under construction or in an advanced planning stage. The Naval Observatory Astrometric Interferometer and the Big Optical Array are sponsored by the DOD. A design study at the Center for High Angular Resolution Astronomy at GSU has led to a plan for an interferometric array of small telescopes.

Owing in part to the terrestrial atmosphere, qualitatively different interferometric issues arise at visible and infrared wavelengths, with heterodyne and direct correlation, and for small and medium telescopes. Therefore, we give highest priority to supporting a multiplicity of projects; there is no other way to engage an adequate community of experimentalists and to train students for the development of the field. Similarly, progress on scientific issues over a wide front will require several operational arrays.

We recommend support for existing small interferometers and development of larger ones. These will further the understanding of technical issues, and will directly yield significant scientific benefits in the measurement of stellar diameters, binary star parameters, and many other areas of predominantly stellar astronomy. We recommend the construction of at least one array of approximately five telescopes of approximately 2 meter aperture, with baselines of at least 100 meters, for demonstration and use in infrared imaging. This will enable the systematic study of star formation, reconnaissance of the outer structure of AGN's, and many other topics involving moderately faint sources.

The proposed programs for the 1990's will lay the foundation for an advanced IR/optical array in the next decade. For such an array a considerable number of apertures, with a total collecting area comparable to a 16 meter filled aperture telescope, and an actual unfilled aperture size of many hundreds of meters, are envisaged. This project, a Very Large Optical Array, will extend ground-based optical interferometry to its faint limit, and will probably have a snapshot capability. We cannot at this time specify the VLOA in any detail. However, serious planning and design can and should begin later in this decade, with the objective of preparing a plan and proposal for the next decade survey ten years from now. This recommendation finds support in the long range planning efforts of NSF's ACAST (Long Range Planning Subcommittees, 1990).

The current DOD and private funding for optical interferometry is critically important, but requires

significant augmentation, including non-DOD national funds. The experimental projects recommended for the 1990's should reasonably be concentrated in the university community, where cost-sharing is readily arranged, and where students will have maximum participation. The VLOA of the next decade will be a unique facility, and would appropriately have national sponsorship and community access.

A Space Program

The Interferometry Panel finds that there is great scientific potential in space-based optical interferometry. Much of the required technology is either in hand or rapidly emerging, but some specific technologies require development. This work should be started in the early 1990's so as to be ready to support a field that is ripe for productive scientific exploitation. We envision an orderly progression from small to large instruments, with the experience gained in the construction of ground-based imaging and astrometric interferometers and large aperture telescopes playing a significant role in the design of the large imaging instruments in space that we recommend for the 21st Century. The recommended progression has three steps: (1) an astrometric mission; (2) a multi-aperture imager (30-100 m baseline); and (3) a major imaging facility with a synthesized aperture of at least one km. These recommendations correspond to components of the recommended post-1995 astronomy and astrophysics program reported by the Space Science Board (1988). It is also consistent with the recommendations of NASA's Planetary System Science Working Group (see Appendix).

(1) *During the 1990's we should design and build the first space-based optical interferometer.* This should be an astrometric instrument of the Explorer or intermediate class with a measurement accuracy goal of a few μsec , and certainly better than 30 μsec . Such an instrument would be a powerful new multi-disciplinary tool for astronomical research. It could open new areas of astrophysical investigation and change the nature of the questions being asked in some old areas. It would address several pressing scientific questions ranging from the existence (or absence), prevalence, and characteristics of extra-solar planetary systems, to galactic structure, mass, and mass distribution. It should directly determine the Cepheid distance scale to better than 2%, would be a potent tool for the detection of planetary systems out to at least 200 pc, and could perform a stringent test of general relativity. The importance of such an instrument has been recognized previously by the scientific community in various NASA and National Academy reports (Space Science Board, 1981; Physics Survey Committee, 1986; Space Astronomy MOWG, 1981).

Although much valuable work could be done with a narrow-angle instrument, there is a considerable advantage to an interferometer that can directly measure large target separations. Such capability opens the way for the determination and correction of instrument bias via 360 degree closure as well as for direct parallax determination without need for a zero-parallax reference object. This is important since, in the case of narrow angle astrometry, finding and certifying a zero parallax object for use with a chosen target in conjunction with μsec astrometric measurements poses problems that arise both because of the small (few square arcmin) field of view for reference objects and because in some directions (e.g., the galactic center) extragalactic objects are obscured. Similarly, measuring the proper motion of and within globular clusters is facilitated by being able to use reference objects outside of the cluster-obscured region.

For a wide-angle instrument and a given target star, the field available for the reference star is generally large and may approach a steradian. Thus a small set of well studied, bright stars ($V \simeq 10$) can serve as reference objects for most observations. Sufficiently redundant observations within the reference set will yield a rigid frame in which the separation would be known a posteriori for any pair of stars, even those not simultaneously observed. Within the reference set, every star becomes a reference for every other star. Thus this frame could be tied to both the extra-galactic frame and the radio frame by a modest number of observations.

For a wide-angle instrument and a given astrometric target (star, asteroid, QSO etc) the field available for reference or comparison objects is large and may approach a steradian. Access is thus ensured to selected reference sources, including distant extra-galactic, zero parallax, zero proper motion objects, well studied stars, and other program sources, allowing all to be tied into a rigid frame.

(2) *During the 1990's we should develop the technology for an imaging interferometer that could be deployed in space early in the next decade.* This logical successor to HST should have a resolution about an order of magnitude greater than HST. Although considerable analysis is required before the architecture of such an instrument is established, we project that it will have a maximum baseline length of at least 30 and

possibly as much as 100 m, and total collecting area comparable to HST. The aperture might consist of 20 or more individual segments, arranged in a configuration determined by a tradeoff of resolution, sensitivity, time required to form an image, and other factors.

This intermediate-size instrument would yield a high level of scientific return by virtue both of its order-of-magnitude resolution advance and of its ability to image faint objects. It would benefit from the ongoing work on ground-based imaging interferometers; it would also benefit from the development of the astrometric interferometer.

(3) *During the early part of the next century, it should be possible to build a great imaging interferometer in space.* This km-scale facility with multiple large apertures (say two to six meters) would represent a major undertaking and could serve as the focus for an international scientific collaboration. The most desirable approach for building the great imaging interferometer is not yet clear. There may be considerable economic advantage to building this instrument on the Moon, depending on a clarification of the extent and time scale of the lunar scientific opportunities. A second option is to use separate free-flying spacecraft for each aperture, with the geometry of the array monitored and controlled by laser beams. The array might be located at one of the libration points of the Earth-Moon system or in geosynchronous orbit. This approach may be attractive, provided that it is possible to build such a "floating imager" at moderate cost. A third possibility is to connect the individual aperture modules by long beams. Studies of the different options will be necessary during the 1990's in order to identify the optimum approach.

Compensating for the Atmosphere with Adaptive Optics

The attainment of diffraction limited imaging is perhaps the most important challenge in ground-based astronomical instrumentation. Over the last 350 years, we have improved the sensitivity of our telescopes 10 million-fold, but at optical wavelengths atmospheric turbulence still prevents the resolution of even the largest telescopes from consistently exceeding that of a telescope with an aperture of only a few inches. We need high angular resolution in astronomy for the information available in improved imagery, and to reach fainter limiting magnitudes.

Many astronomical objects have structure much less than an arcsecond in scale. Such objects include all distant galaxies, the cores of normal and active galaxies, regions of dense star formation, most circumstellar disks, and all but the most gross features of planets. The Hubble Space Telescope should provide dramatic improvements in visible and UV spatial resolution, but only modest improvements in the infrared. However, an 8 meter ground-based telescope equipped with adaptive optics will provide angular resolution at $2\ \mu\text{m}$ equal to the resolution of HST at $0.5\ \mu\text{m}$. Although adaptive optics will improve the performance of ground-based telescopes at all wavelengths, the gains in the infrared will probably be the most productive for astronomy in the 1990's, and the infrared science objectives are emphasized here.

Some of the most exciting applications of adaptive optics will be in the imaging and spectroscopy of galaxies. AGN's and the cores of "normal" galaxies are especially amenable to study with this technique. For instance, measurements of velocity dispersion near the center of normal galaxies such as M31 or M32 indicate that they may contain $10^7\ M_{\odot}$ black holes. Such data can be checked and extended to other nearby galaxies by using adaptive optics to carry out high spatial resolution spectroscopy. The central regions of galaxies are clearly special, and an 8 meter telescope will be able to explore these out to 3 Mpc with a resolution of 1 parsec. A 3.5 meter telescope should be able to resolve spiral arms anywhere in the universe. The surface brightness of an elliptical galaxy is very high, and it should be possible to carry out spatially resolved, velocity dispersion measurements for distant elliptical galaxies, enabling us for the first time to study the dynamics of galaxies in an earlier stage of evolution.

Supernova searches can be extended to high redshift galaxies by working in the infrared with adaptive optics. Even more exciting, especially for 8 meter telescopes, is the possibility of detecting very distant supernovae. Since SN probably occur before a galaxy forms a disk, we may see SN from primordial galaxies before we see the galaxies themselves. Also, it may be easier to detect a time-variable point source than a very low surface brightness extended source. The detection rate for SN at $z=1$ to 3 would be low for the local SN rate, but could be in the range 1/night of observation if the star formation rate in primordial galaxies were as large as $60\ M_{\odot}$ per year.

Large telescopes with adaptive optics will allow us to explore the morphology and kinematic structure of circumstellar disks, especially around late-type stars. These observations, essential for studies of stellar and

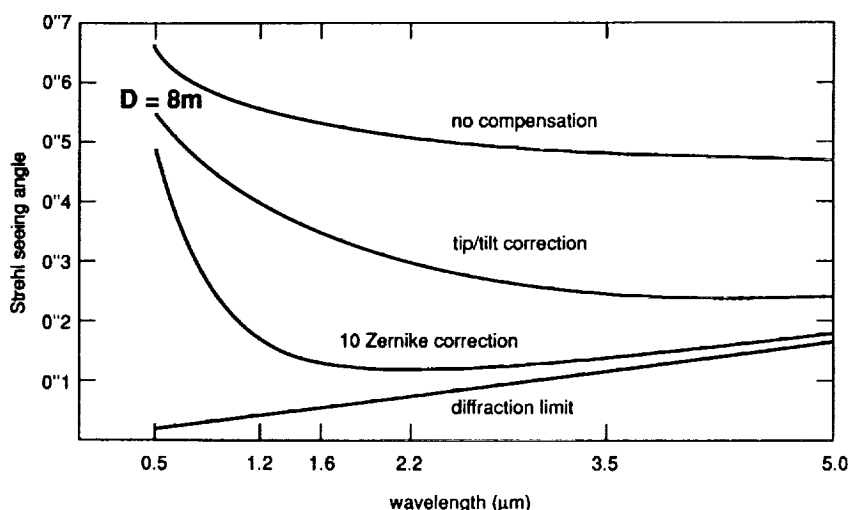
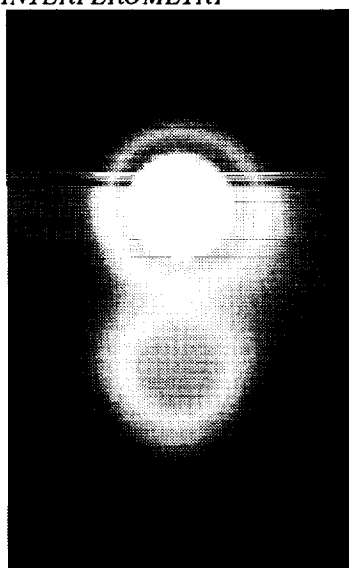


Figure 4 (left). A demonstration of diffraction limited imaging at $2.2 \mu\text{m}$ with adaptive optics and a 1.5 m telescope. The image is of the binary γ_2 Ari, separation $0.55''$ (Rousset et al, 1990).

Figure 5 (right). The calculated seeing width as a function of wavelength for an 8 m telescope with various degrees of adaptive compensation. The uncompensated Strehl width at $0.5 \mu\text{m}$ is assumed to be 0.66 arcsec . (F. Roddier, private communication)

planetary formation, can be achieved from ground-based telescopes. IR speckle observations have already shown the existence of infalling halos with solar system size inner diameters around stars such as HL Tau and R Mon. Adaptive optics allows us to explore such structures with a resolution of 10 AU for the nearest, with sufficient sensitivity to study a representative sample of objects with different ages. Studies of the circumstellar gas kinematics are necessary to determine how stars and planets form. Keplerian velocities are of the order of 10 km/sec, so we need spectral resolution of 100,000 and high spatial resolution to determine whether matter is falling into or leaving the star. Emission from the CO molecule at $4.8 \mu\text{m}$ should be well suited for this measurement.

Another important problem is the initial mass function of young stars as they condense from clouds of gas and dust. The IMF is crucial for many studies of star formation and galaxy evolution. In the Orion molecular cloud OMC1, the separation between stars at the present detection limit is a few arcseconds, and many of these are multiple. High spatial resolution is needed to obtain the HR diagram.

Brown dwarfs are objects too small to initiate hydrogen burning. Although there are strong theoretical grounds for their existence in large numbers, no confirmed detection has been yet made. Since the dwarf is close to the brighter primary, high angular resolution and dynamic range are required. With adaptive optics and an expected dynamic range of 9 magnitudes it should be possible to detect 40-50 Jupiter-mass objects out to a distance of at least 5 pc. This is a comparable sensitivity to the complementary technique of Doppler measurements (Latham et al, 1989).

For point objects improvements in seeing scale directly into improvements in limiting flux, owing to the reduction of background possible with improved concentration of light in a point source image. Higher angular resolution on large telescopes is in fact the most cost-effective way of observing fainter point objects. Thus a diffraction limited 3.5 meter telescope can in principle reach the same limiting flux as a 30 meter seeing limited telescope in the visible. Incorporation of diffraction limited imaging on an 8 meter telescope extends its limiting flux by more than an order of magnitude in the near infra-red.

The method of adaptive optics includes all orders of wavefront correction, beginning with the simplest, tilt correction (similar to fast guiding). The order of correction employed, and the resulting image improvement, will depend on the wavelength and telescope diameter. Thus in the infrared, low order correction alone may achieve near diffraction limited images, while at shorter wavelengths low order correction will provide improved image quality, while still far from the diffraction limit.

A major limitation of adaptive optics is the limited field of view over which the technique is applicable. Light from two sources in the sky travels through different turbulence and our ability to correct the

wavefront over an appreciable field is limited by this effect. The region over which the optical properties of the atmosphere are correlated is called the isoplanatic patch. The size of the isoplanatic patch is a serious problem since often the target object itself is too faint to readily determine the instantaneous atmospheric wavefront. A nearby bright source must serve this function. We can then only observe bright objects or objects that happen to be near a bright star. The probability of finding a bright enough guide star within the isoplanatic patch varies with wavelength, so that in the infrared we can indeed use an off-axis guide star to make the complete corrections. The area of sky which can be covered depends strongly on the order of correction desired and the wavelength, and varies from near 100% at $10\ \mu\text{m}$ (large isoplanatic angle, large time constant) to less than 1% at $0.5\ \mu\text{m}$ (isoplanatic angle of only a few arcsec, short time constant). For low orders of wavefront distortion, such as would be compensated with partial adaptive correction, the correlation extends over much larger angles. Thus, for example, for tilt error, with an 8-meter telescope, the correlation coefficient should exceed 0.5 over angles of several hundred arcsec (this angle depends on the model of the atmosphere, seeing, etc).

To overcome the need for a nearby astronomical reference source Foy and Labeyrie proposed, in 1985, to generate an artificial star by focusing a single frequency laser in the Sodium layer of the upper atmosphere. The laser-generated artificial star could then be positioned near any object in the sky. The major technical problem are the laser and the correction of many elements in the aperture for work in the visible. An artificial reference source cannot provide a measurement of the lowest order errors, the piston (relevant only for interferometry) or the tilt, thus a celestial reference source is still required. However, with an artificial reference source to ensure a plane wavefront across the telescope aperture, a much fainter celestial reference may be used, and only low order information is required of it.

A Program for Development and Implementation of Adaptive Optics

A large and continuing DOD investment goes into adaptive optics. This effort represents an important potential resource for astronomy, although actual DOD systems may be too complex, expensive, or specialized for wide implementation in astronomy. Although several sources are available for the principal components of adaptive optics systems, turnkey or blackbox systems are not currently feasible or desirable. The astronomy community must develop the expertise to build and utilize these relatively complex systems.

Several groups in the U.S. are currently working with adaptive optics for astronomy. These include NOAO (solar and stellar programs), Johns Hopkins (adaptive optics with coronagraphy), the University of Chicago and University of Illinois (laser reference techniques), University of Hawaii (wavefront sensing, adaptive mirrors), and Steward Observatory (neural net processing, adaptive systems). Such programs are important to development, adaptation, and implementation of technology and training of students. Support is required to continue and expand such activities.

We recommend support during the 1990's for the implementation of adaptive optics on a number of telescopes, particularly including large telescopes, where the potential gains are greatest. The early years of the program should emphasize the areas of infrared imaging and spectroscopy and solar astronomy. The scientific return in these areas is expected to be readily achieved, once adequate resources are made available. Later in the decade, more sophisticated systems will extend diffraction-limited visible performance to large telescopes. Combined with the multi-telescope interferometry programs described above, AO will yield a large gain in performance of distributed optical arrays.

Adaptive Optics is a revolutionary and cost effective emerging advance in ground-based astronomical instrumentation. At the moment it suffers from a high entrance fee in terms of intellectual investment and capital. We can target five areas which need support over the next decade.

- 1 *Rapid demonstration of partial correction.* Adaptive optics systems with 10-100 actuators may be demonstrated and used extensively for science during the next five years. These will be near state of the art and will be implemented initially for solar work at visible wavelengths and for 3-4 meter class telescopes in the infrared.
- 2 *Development of lower cost systems.* It should be possible to develop moderate cost adaptive systems oriented to astronomers requirements. Our objective should be to extend the most useful benefits of adaptive optics to many telescopes and interferometric arrays at a cost not much different from a major instrument. The key here is the development of new types of hardy, cost-effective adaptive mirrors and

wavefront sensors. Membrane mirrors, bimorph mirrors, and curvature sensing are techniques which appear promising. These systems will probably be built by astronomers at their home institutions.

- 3 *Laser reference systems.* Implementation of high order adaptive correction, or extension to faint sources of partial correction at visible wavelengths, will require laser reference systems. It will be a challenge to devise cost-effective implementations of these potentially expensive techniques for use in astronomy. Such work may use hardware developed for military systems, and may profit from collaboration with experienced DOD contractors.
- 4 *Algorithms.* The development and application of mathematical techniques is required both to control the system and to improve the images once they have been detected. Although much of the light can be contained in the outer halo of the point spread function, especially at shorter wavelengths with partial correction, simulations show that the halo is smooth and has low surface brightness after a long exposure. Deconvolution and contrast enhancement methods, such as the van Cittert or more powerful non-linear techniques similar to those used by radio astronomers, can dramatically improve the dynamic range of the processed images.
- 5 *The training of an adequate core of personnel.* Adaptive optics systems are complex. Small errors in understanding can and have invalidated some work. DOD systems often have a near permanent staff from the manufacturers to keep the sub-systems running. At observatories at least some staff on the mountain must be well informed and able to adjust, service, and improve the systems.

At present the only working adaptive optics system in night time astronomy (excepting simple tip/tilt correction) is in Europe. Funding and support of this technology is essential to maintaining the competitiveness of existing U.S. telescopes, even of the 8-m telescopes that are on the drawing board. The cost of a balanced program in the U.S. is estimated at \$35 million over the next ten years, less than the cost of a single large facility.

Gravitational Waves

Observations of the inspiral rate for the binary pulsar PSR 1913+16 have given strong support to the predictions of general relativity for the strength of gravitational radiation from accelerating massive bodies. Valuable limits on the intensity of gravitational waves reaching the Earth have been set by a combination of terrestrial antennas of different kinds, including Doppler tracking of distant spacecraft and timing measurements on millisecond pulsars. We will describe here two proposed gravitational wave observatories using laser interferometers as broadband antennas, and the opportunities for obtaining entirely new types of astrophysical information with them.

One proposed observatory is LIGO (the Laser-Interferometer Gravitational-Wave Observatory), a high-frequency, earth-based project, which is now nearing the end of a decade-long planning, design, and research and development stage. This project would construct a vacuum facility to support many generations of gravitational-wave detectors, and would construct an initial detector system. Construction of LIGO has been approved by the National Science Board, and funding has been requested from the Congress. The other proposed observatory is LAGOS (the Laser Gravitational-Wave Observatory in Space), for which a preliminary feasibility study has been completed. It will be proposed to NASA for technology development during the 1990's and possible flight in the decade 2000-2010. These observatories would cover the frequency range from roughly 10^4 Hz to 1 Hz (LIGO) and the from 1 Hz to 10^{-5} Hz (LAGOS).

Gravitational waves are emitted by the coherent, bulk motions of large amounts of matter (e.g. collapsing stellar cores) and by coherent, nonlinear vibrations of space-time curvature (e.g. collisions of black holes). The strongest extragalactic waves bathing the earth are not likely to exceed $h \sim 10^{-20}$, where h is the strength of the perturbation in the metric. The strongest sources are likely to be black holes and neutron stars – e.g., the violent births of black holes and neutron stars in stellar implosions, and the inspiral and coalescence of binary neutron stars and black holes in distant galaxies. The characteristic frequencies of vibration and rotation for neutron stars are less than or of order a few kilohertz; and those for a black hole of mass M are

$$f \sim \frac{10k\text{Hz}}{M/2M_{\odot}}$$

(where $2M_{\odot}$ is the smallest possible mass for a black hole that forms by stellar collapse). Thus, the strongest waves are likely to lie at frequencies of 10 kHz and below.

Because the strongest sources are compact concentrations of highly dynamical mass, they typically will lie in regions obscured by surrounding matter (e.g., in the core of a supernova explosion or at the center of a galaxy or in the big-bang origin of the universe). Fortunately, gravitational waves are highly penetrating. For example, primordial gravitational waves should have last scattered near the Planck time, $\sim 10^{-43}$ seconds, when the initial conditions of the universe were being set by the (little understood) laws of quantum gravity

High Frequency Gravitational Wave Sources (LIGO)

Coalescence of neutron-star and black-hole binaries. Of all sources in the LIGO's high-frequency band, the final inspiral of a binary neutron star is best understood: Because the binary orbit is nearly Keplerian, the details of the waves are known with confidence; and binary pulsar observations have provided enough information about birth rates of binary neutron stars to pin down the distance to which one must look in order to see several coalescences per year. That distance is 100 Mpc, give or take a factor of a few. Advanced detectors in the LIGO should be able to detect the inspiral waves out to a distance of about 1000 Mpc, where the event rate is presumably many per year (see Figure 6a).

From measurements of the waveforms emitted by the final inspiral and coalescence, one can extract the masses of both objects. The inspiral waveforms also reveal, directly, the distance to the source – without any assumptions. Thus, such inspirals serve as “standard candles”.

Supernovae. Those supernovae (primarily type II) that are triggered by the collapse of a stellar core to form a neutron star should produce bursts of gravitational waves. Although the rate of such supernovae is well known from electromagnetic studies, the strengths of their waves depend crucially on the unknown degree of asymmetry of the collapse. The LIGO has hope of seeing highly asymmetric collapses ($\sim 10^{-3} M_{\odot} c^2$ radiated) out to the VIRGO cluster, but would have difficulty seeing nearly spherical collapses ($\sim 10^{-10} M_{\odot} c^2$ radiated) even in our own galaxy. Observational studies of the gravitational waves from supernovae could bring information not obtainable in any other way about the asymmetry in the collapse and about the physics of very young neutron stars.

Rotating Neutron Stars. Advanced detectors in the LIGO could detect the gravitational waves from a neutron star anywhere in our galaxy if its equatorial ellipticity exceeds $\epsilon_{\min} \sim 10^{-9} (P_{\text{rot}}/1 \text{ msec})^2$, where P_{rot} is the star's rotation period. If there are many such neutron stars, LIGO will be a rich source of information about neutron-star physics.

When a neutron star with magnetic field $B \simeq 10^7$ Gauss is being spun up by accretion from a companion, the spinup may be halted by an instability triggered by gravitational radiation reaction. Interesting constraints on the viscosity of neutron-star matter (which impedes the growth of the instability) and on the equation of state would follow from observing such objects.

Black – Hole Births. Black holes with masses of a few M_{\odot} up to a few tens of M_{\odot} are thought to be born in the collapses of massive ordinary stars; and more massive holes may be born in galactic nuclei, in collapses of supermassive stars, and/or in star clusters. The rate of such events is highly uncertain (it is not even firmly known that black holes exist); and the mass spectrum of the resulting black holes is highly uncertain. Advanced detectors in the LIGO should be able to detect highly nonspherical black-hole births throughout the universe, for hole masses between 50 M_{\odot} and 1000 M_{\odot} .

Cosmological Studies. Gravitational-wave observations might bring us valuable cosmological information in several areas. One concerns fluctuations in the early universe. Gravitational waves emerging from the Planck era of the big bang – even waves so weak that they are nothing but vacuum fluctuations – can be amplified, during the earliest epochs of the universe's expansion, to make them detectable. The amplification is “parametric”; it results from coupling of the waves to the large-scale background curvature of the expanding space-time. Observations of such waves, or failure to observe them, will provide valuable information or constraints on theories of the very early universe, such as “inflation.” The potential sensitivity of the LIGO is about 10^{-10} of the closure density at frequencies near 30 Hz. For comparison, pulsar timing is now nearing $\Omega_{\text{GW}} \sim 10^{-7}$ at $f \sim 10^{-8}$ Hz; anisotropy of the cosmic microwave background gives limits of $\Omega_{\text{GW}} \sim 10^{-12}$ in a very narrow window at $f \sim 10^{-16}$ Hz; and the time delay in the gravitational lens 0957+561 gives a limit $\Omega_{\text{GW}} \sim 10^{-8}$ at $f \sim 3 \times 10^{-18}$ Hz.

Low Frequency Gravitational Wave Sources (LAGOS)

Binary Stars. The total number of binaries in the galaxy with frequencies between 10^{-5} and 10^{-2} Hz is roughly 10^8 . This includes detached binaries, contact binaries, cataclysmic variables, neutron star binaries, and close white dwarf binaries. The numbers expected are fairly well known, except for the close white dwarf binaries, which have not yet been observed. Specific predictions of the number density of white dwarf binaries are available but are highly uncertain, in part because such binaries must undergo two periods of common envelope evolution during their history, and could be disrupted. Evolutionary calculations suggest that substantial numbers of black hole-neutron star binaries may also be present.

The number density of binaries in our galaxy drops off rapidly at higher frequencies, and at some frequency near 10^{-3} Hz there will be less than one binary per cycle-per-year frequency bin. Somewhat above this frequency, most binaries will be clearly resolved, and their locations can be determined by analyzing the change in signal strength as they go through the sharp nulls in the antenna pattern. The highest frequency galactic binary signals are expected to be about 3×10^{-3} Hz for neutron star binaries, and about 2×10^{-2} Hz for close white dwarf binaries if they are present at 10% of the calculated number density. The strengths of the expected signals for these two types of binaries are shown in Figure 6b. Below 10^{-3} Hz, some binaries which happen to be unusually close will be observable above the unresolved galactic binaries.

Information concerning the unresolved galactic binaries can be obtained from the shape of the observed spectrum. However, these binaries also provide noise, which makes it more difficult to observe other kinds of signals such as possible extragalactic backgrounds and possible coalescence signals from active galactic nuclei. The unresolved galactic binary signal strength is shown in Figures 6a-c, both without close white dwarf binaries (solid curves) and with 10% of the calculated number density for them (dotted curves). If the close white dwarf binaries are present at nearly the calculated level, an isotropic stochastic background signal should be observable between 10^{-3} and 10^{-2} Hz due to the integrated signal from all the other galaxies. Each shell of a given thickness contributes roughly equally on the average, so the signal would come from sources nearly all the way out to the Hubble radius.

Coalescence signals from AGN's. Probably the most interesting burst source for LAGOS is inspiral signals from white dwarfs, neutron stars or $\sim 10M_{\odot}$ black holes orbiting around central supermassive black holes (SMBH's) in AGN's or quasars. If perhaps 10% of the AGN or quasar core immediately after SMBH formation is in such compact objects, inspiral signals may be observable between 0.3 and 10 millihertz during the period while the SMBH is growing to roughly $10^7 M_{\odot}$. However, if close white dwarf binaries are present at nearly the calculated density, fluctuations in the integrated signal from many of them will limit the antenna sensitivity. In this case, the range of frequencies and distances over which signals could be observed would be limited, and the event rate would be reduced.

Cosmological backgrounds. The sensitivity of LAGOS in searching for cosmological backgrounds such as possible amplified relic gravitons from inflation would again depend on the strength of the noise background from close white dwarf binaries. For a density of such sources which is 10% of the calculated value, the sensitivity would be about 10^{-11} of the closure density. However, with few close white dwarf binaries, the sensitivity would be roughly 100 times better.

A Gravitational Wave Observatory Program

A laser interferometer gravitational-wave detector, in its simplest conceptual variant, consists of masses that hang by wires at the corner and ends of an L. A gravitational wave pushes the masses back and forth relative to each other, changing the difference in the length of the detector's two arms by an amount ΔL that is proportional to the arm length L and to the strength of the metric perturbation h . By laser interferometry one directly reads out $\Delta L/L$ and, from its time evolution, the waveform $h(t)$. The interferometry is typically done in one of two ways: each arm is operated as a delay line, with a light beam bouncing back and forth in it many times, or each arm is operated as a giant Fabry-Perot cavity with finesse as large as 10,000.

More sophisticated optical configurations, called "broad-band recycling," "dual recycling," and "resonant recycling" have the potential to improve the sensitivities markedly.

For most noise sources (e.g. seismic noise, gravity gradient noise, and thermal noise, which dominate at frequencies $f \leq 100$ Hz), the displacement noise ΔL in the interferometer is independent of the arm length L ; and, correspondingly, the gravitational-wave sensitivity $h = \Delta L/L$ improves with increasing arm length. Prototype interferometric detectors, with arm lengths from 1 meter to 40 meters, have been under development since 1970 and vigorously since about 1976. Feasibility studies, technology development, and planning for full-scale detectors have been carried out in the United States since 1981, with funding from NSF. In 1984 plans were initiated for the design, construction, and operation of a full-scale system called the LIGO; and in 1986 the Physics Survey Committee ("Brinkman Committee") strongly endorsed the LIGO.

The unequivocal ground-based detection of gravitational-wave bursts amidst instrumental and environmental noise requires cross correlation of two detectors at widely separated sites. For this reason, the LIGO will include two facilities, far apart in the continental United States, in which cross correlated detectors will operate. To determine the direction to a source and to separate its two polarizations (i.e. to extract the full details of the wave) will require cross correlating three, and preferably four detectors at widely separated sites. The American effort will have to rely on similar detectors in Europe, Japan, and/or Australia for the third and fourth detectors of a world-wide network. Numerical simulations of such a network predict, for gravitational-wave bursts, angular resolutions of a few tens of arc minutes for interesting sources.

Figures 6a-c show the expected sensitivities of (i) the first detectors planned for the LIGO, and (ii) more advanced detectors that might operate in the LIGO a few years after the first ones. The technology for the advanced detectors is expected to be well in hand within the next several years, but key aspects of their design cannot be tested adequately in the existing 40-meter prototype vacuum system, and must await the full scale LIGO.

The development and operation of a network of resonant acoustic bar detectors should continue to be supported. The detectors are approaching sensitivities which could detect galactic supernovae. The present prototype interferometric detectors, although beginning to rival the sensitivity of current bar detectors, will not be operated in observational mode during the development of the large baseline systems.

Laser Gravitational Wave Observatory in Space

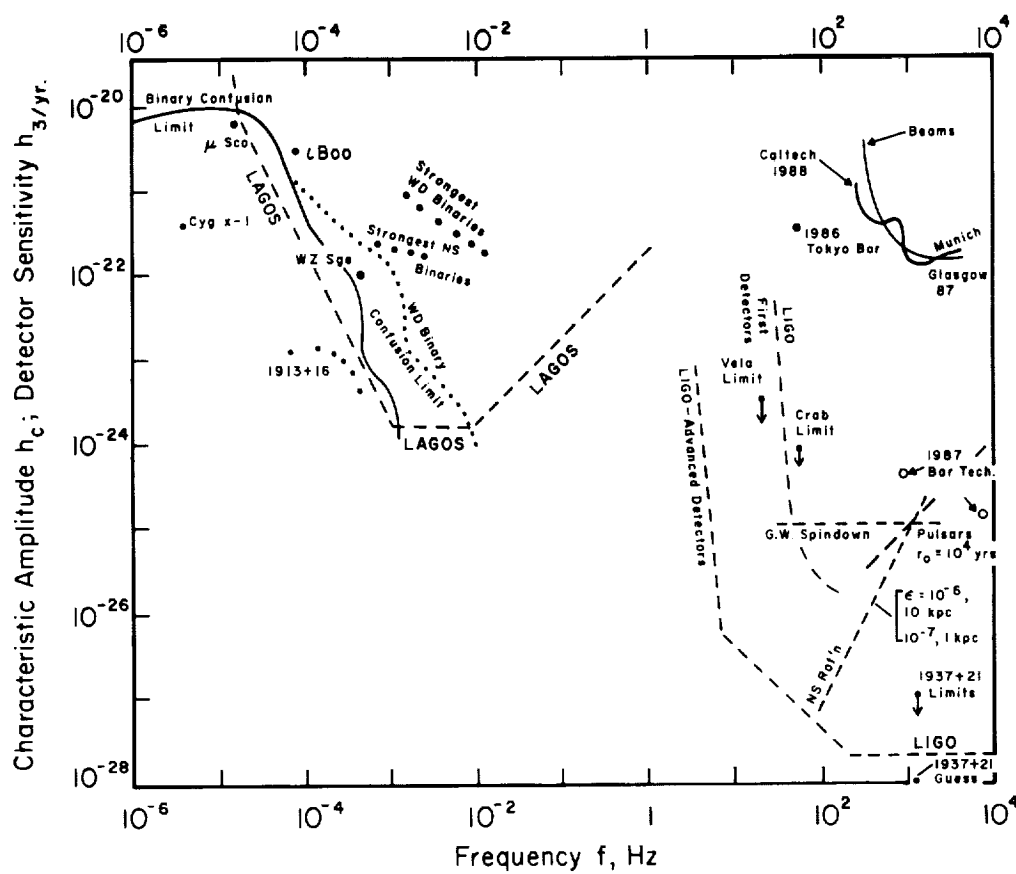
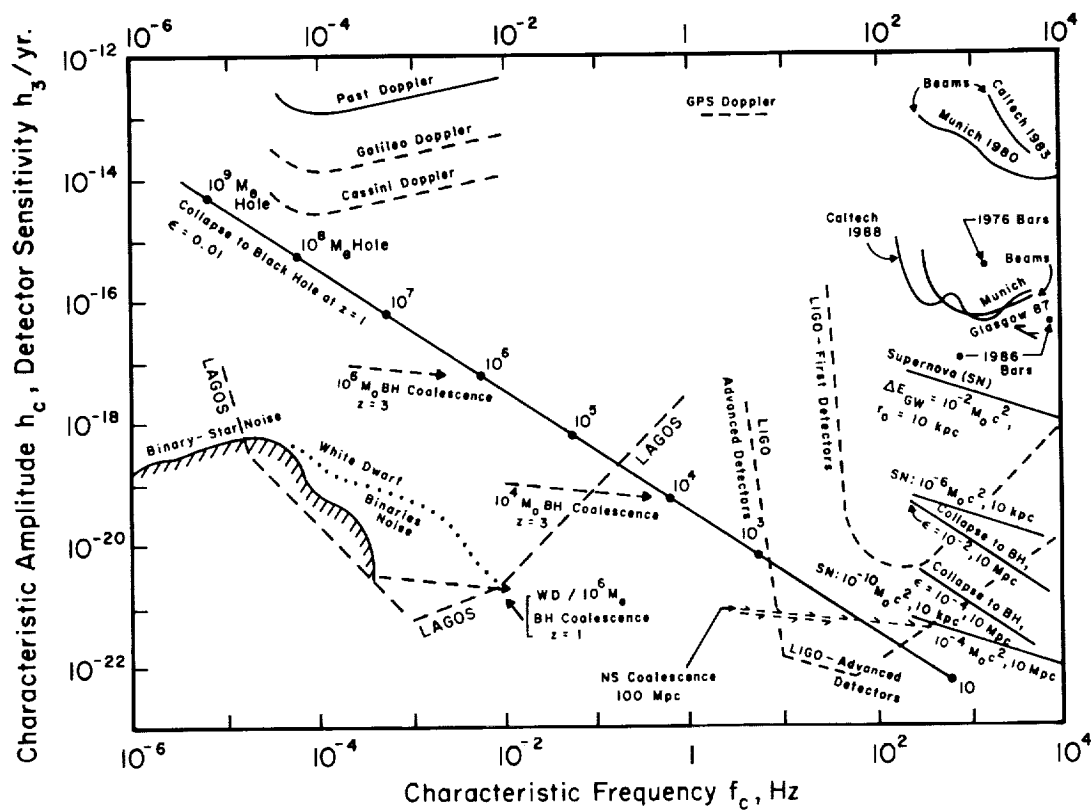
Ground-based interferometric detectors cannot be used in the low-frequency band because displacement noise for their test masses is an insurmountable problem at low frequencies. To achieve high sensitivity in this band requires an interferometer in space with very large arm lengths. The proposed LAGOS antenna makes use of carefully shielded test masses freely floating inside three separate spacecraft, which are 10^7 km apart. The cluster of three spacecraft is located near the L-5 point of the Earth-Sun system. The lengths of the two interferometer arms will remain equal to 0.2% for proper choices of the initial orbit parameters.

Changes in the test mass separations are monitored by laser phase measurements. One watt of power from a cavity-stabilized Nd-YAG laser pumped by laser diodes is sent out from the central spacecraft to each end spacecraft through 0.3 m telescopes. Similar lasers in each end spacecraft are phase-locked to the received signal and transmit back to the central spacecraft. The phase of the returned signals is measured as a function of time with respect to the laser in the central spacecraft.

To the extent that the test masses can be protected from spurious accelerations at frequencies of 10^{-5} to 1 Hz, laser wavelength variations can be corrected for by measuring the sum of the apparent variations in length for the two interferometer arms. The corrected laser wavelength is then used to determine changes in the difference in arm lengths due to gravitational waves and instrumental noise. The effect of the residual laser wavelength variations is reduced because they are nearly common mode for the two arms. This correction procedure works at all frequencies in the range of interest, except for narrow bands around harmonics of the 0.017 Hz round-trip frequency for one arm.

The expected antenna performance is shown in Figures 6a-c. The best performance is achieved for frequencies between 10^{-3} and 10^{-2} Hz. The performance gets worse above 10^{-2} Hz because of the gravitational wavelength getting shorter than the arm length, and worse below 10^{-3} Hz because of spurious accelerations of the test masses and thermal fluctuations in the telescope. The performance degrades even more rapidly below about 2×10^{-5} Hz because the thermal isolation becomes inadequate.

A single antenna in space should be sufficient for measuring most kinds of expected low-frequency



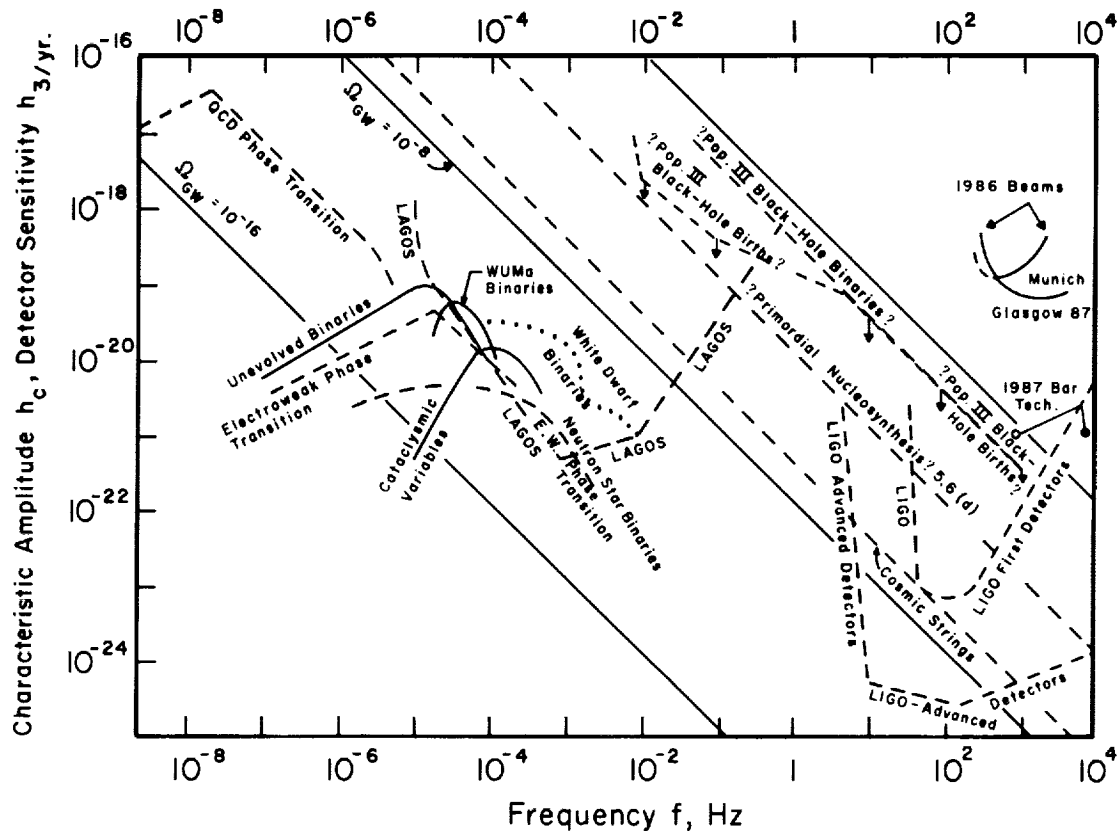


Figure 6a (opposite, top) Gravitational-wave bursts: estimated source strengths and detector sensitivities. Plotted vertically are the characteristic amplitudes h_c of gravitational waves from several postulated burst sources and the sensitivities of several existing and planned detectors. Abbreviations are BH, NS, and SN are used for black hole, neutron star, and supernova. The sensitivities are for 90% confidence of detecting very rare bursts.

Figure 6b (opposite, bottom) Periodic gravitational waves, and detector sensitivities for 90% confidence of detection in 10^7 seconds of integration time.

Figure 6c (above) Stochastic gravitational waves and detector sensitivities. (These figures adapted from Thorne, 1987, where additional discussion will be found.)

gravitational wave signals. Periodic signals from roughly 10^3 binary stars in our galaxy, near 10^{-3} Hz and possibly up to 10^{-2} Hz, should be easily observed. Below about 10^{-3} Hz, there will be a random superposition of signals from roughly 10^8 binary stars in our galaxy, which cannot be resolved in frequency even with a few years of data. However, the passage of the galactic center through the nulls in the antenna pattern four times a year will verify that the detected spectral amplitude curve is not due to unexpected instrumental effects. It is only for isotropic extragalactic background that the limitation of having a single antenna is likely to be substantial.

Until the LAGOS antenna is developed, the principal technique for searching for low frequency gravitational waves will continue to be Doppler tracking of distant spacecraft using microwave transponders. The sensitivity will be increased substantially by tracking in X-band on both uplink and downlink, a step to be taken for the first time with the Galileo mission; and can be increased still further by tracking at Ka-band, as is being considered for the Cassini mission. Since searching for gravitational waves is a small additional cost for missions to the outer planets, we recommend continuing to carry out searches with future missions, especially those that will have Doppler capabilities at X-band and/or at higher frequencies.

Technology Development During the 1990's

Conceptual design studies for LAGOS were carried out during 1985-1988 under the NASA Innovative

Research Program. Preliminary technology development studies were started in 1989. The present mass estimates are 200 kg on-orbit mass each for the two end spacecraft and 400 kg for the central one.

There are several areas in which major technology development is required. The first is the development of a very low thrust station-keeping and altitude-control propulsion system. The thrust levels required are far below those for any previous mission, but are needed continuously to counteract solar radiation pressure on the spacecraft, so high fuel efficiency is desired in order to permit a 10 yr mission lifetime. The primary requirements on the system are that it keep the spacecraft centered on the test mass, and that it maintain the spacecraft orientation accurately with respect to the laser beam transmitted by one of the other spacecraft.

A Disturbance Reduction System is needed to protect the test mass inside each spacecraft from spurious accelerations which could mask the effects of gravitational waves. The requirement is to keep the fluctuations of the spurious test mass accelerations about 6 orders of magnitude below the acceleration an uncorrected spacecraft would have due to variations in the solar radiation intensity and in the solar wind.

LAGOS requires construction and space-qualification of 1 Watt stable lasers with long lifetime and high efficiency. The development of diode-pumped Nd-YAG lasers has been proceeding rapidly, and a five year lifetime for each laser with about 15% efficiency and high reliability appears feasible. The lasers would be locked to rugged Fabry-Perot interferometers with low expansion spacers and optically contacted mirrors to provide good short-term stability.

Two other areas are the development of a high-stability laser beam steering system and the investigation of improved thermal insulation methods.

A gravitational wave antenna to go on the Moon soon after the year 2000 also has been proposed. By working with LIGO and with other terrestrial antennas, it would improve the angular sensitivity for determining the location of burst sources. Such a lunar antenna also would require technology development during the 1990s. The frequency range would be from perhaps 0.3 Hz to a few kHz.

Prospects for International Collaboration

International collaboration is likely to play a role in the larger projects recommended here. We note that there is considerable interest in the European space community in astrometry from space (viz. Hipparcos) and an imaging interferometer features prominently in the ESA Horizon 2000 program.

The search for gravitational radiation and especially the full development of gravitational wave astronomy would benefit from a worldwide network of interferometers to gain source position and wave polarization information. On-going efforts in Europe and proposed programs in Australia and Japan are to be encouraged.

Related Issues

(1) Adaptive optics and optical interferometry require imaging detectors of the highest quantum efficiency and lowest noise. This requirement is strongly driven by the need to detect position and phase reference information within an atmospheric time constant, usually much less than a second.

(2) The large telescopes planned for this decade could constitute a unique resource for interferometric experiments or instruments of the future, provided some consideration is given to their siting and configuration in the planning and construction phase.

(3) The transfer of technology from DOD to the astronomy community is important to the timely and cost-effective development of adaptive optics for astronomy.

(4) The Explorer program has a nominal cap for total mission cost to launch of \$100M. There is a large gap between this level and the level of a typical "new start" taken to congress. This inhibits scientifically important missions which naturally fall in this cost range, as an Astrometric Mission probably does.

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Appendix - PSSWG Statement for the Interferometry Panel

The Planetary System Science Working Group (PSSWG) was formed by G. Briggs (NASA SL) in early 1988 to investigate means of detecting and characterizing extra-solar planetary systems. The PSSWG, under the chairmanship of B. Burke (MIT), expanded its role to include studies of the nature of planetary systems and the relation between their formation and formation of stars. This scope includes the physics of pre-planetary nebulae and circumstellar envelopes, and is closely related to the domain of the newly formed "origins" program.

In addressing scientific goals, PSSWG has concluded that the determination of the prevalence and natures of other planetary systems, in a broadly based study, is essential to an understanding of how such systems form and evolve. Further, such a study would eventually show whether our own Earth is a rare exemplar or one of myriad planets in our Galaxy that could support life. The study will require more than one generation of interferometric instrumentation, with successive generations permitting deeper searches. For studies of nearby stars, the stages might include (in order of challenge): Jupiter-sized planets three to ten AU from their stars; Uranus-sized planets in the water-ice condensation zone; and Earth-sized planets at one to two AU from their stars. At each stage, it is essential that the search "drain the lake," not just provide a "fishing expedition."

PSSWG has considered both short-term (next ten years) and long-term (following twenty years) strategies. In the short term, the prime objective would be the discovery of extra-solar planetary systems. An essential characteristic of any system chosen for this task is that a negative result be scientifically valid. As this new phase of planetary science develops, the work would aim at the preliminary characterization of the systems discovered and the statistical study of the kinds of stars that support planetary systems. The PSSWG has found that, considering the instruments that could be built in the short term, the principal approach for reliable detection of extra-solar planetary systems is by means of space-based astrometry. In particular, the goal of detecting a Uranus-sized planet having a radial separation of five AU appears to be beyond the range of ground-based techniques. However, with space-based instrumentation, it would be possible to achieve orders of magnitude improvement over the present ground-based astrometric accuracy of a few mas. Thus, this critical test is within reach and should be performed. The groundwork should also be prepared for developing more advanced interferometric systems that can carry out the in-depth planetary systems studies that will develop in the following decades.

FIGURE CREDITS

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